Fundamentals of Control Systems

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4

Fundamentals of Control Systems

4.1 Objectives

This chapter reviews the basic principles of process control.

As a result of studying this chapter, and after having completed the relevant exercises, the student should be able to:

Clearly explain the concepts of:
- On-off Control
- Modulating Control
- Open Loop Control
- Ratio Control
- List the ten most common acronyms and basic terminology used in the process control (e.g. PV, MV, OP);
- Describe the differences between a reverse and a direct acting controller;
- Indicate what deadtime is and how it impacts on a process.

4.2 ON-OFF control

The oldest strategy for control is to use a switch giving simple on-off control, as illustrated in Figure 4.1. This is a discontinuous form of control action, and is also referred to as two-position control. The technique is crude, but can be a cheap and effective method of control if a fairly large fluctuation of the process variable (PV) is acceptable.

A perfect on-off controller is 'on' when the measurement is below the set point (SP) and the manipulated variable (MV) is at its maximum value. Above the SP, the controller is 'off' and the MV is a minimum.

On-off control is widely used in both industrial and domestic applications. Most people are familiar with the technique as it is commonly used in home heating systems and domestic water heaters. Consider the control action on a domestic gas fired boiler for example. When the temperature is below the Setpoint, the fuel is 'on'; when the temperature rises above the Setpoint, the fuel is 'off', as illustrated in Figure 4.2.

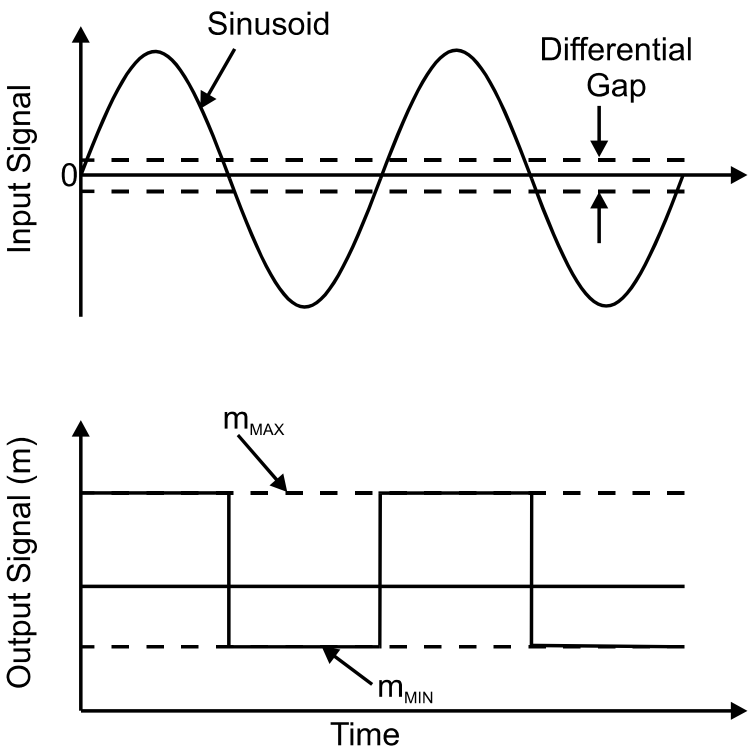


Figure 4.1
Response of a two positional controller to a sinusoidal input

There is usually a dead zone due to mechanical delays in the process. This is often deliberately introduced to reduce the frequency of operation and wear on the components. The end result of this mode of control is that the temperature will oscillate about the required value.

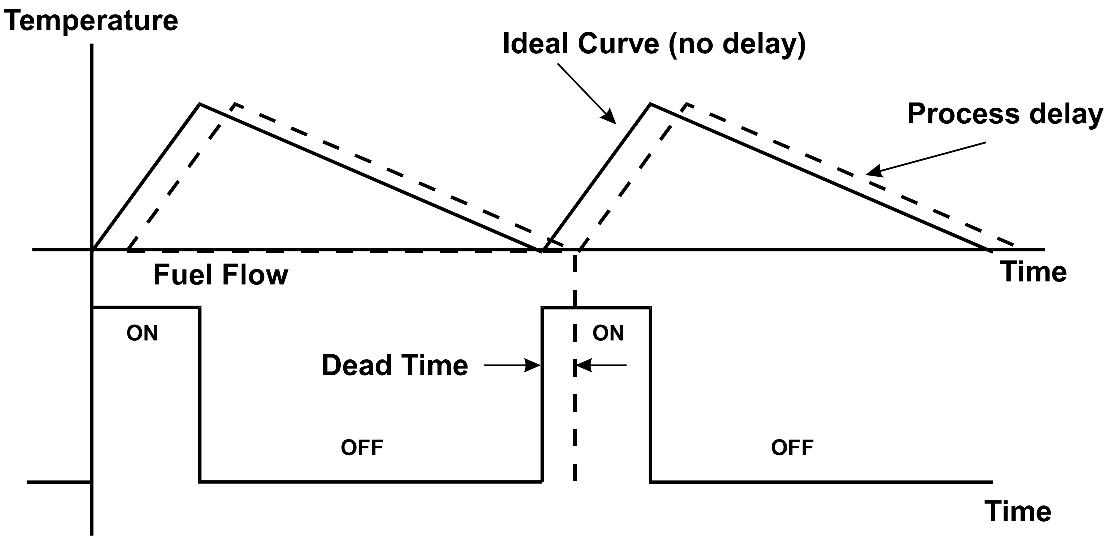


Figure 4.2
Graphical example of ON-OFF control

4.3 Modulating control

If the output of a controller can move through a range of values, this is modulating control.

Modulation Control takes place within a defined operating range only.

That is, it must have upper and lower limits. Modulating control is a smoother form of control than step control. It can be used in both open loop and closed loop control systems.

4.4 Open loop control

In open loop control, the control action (Controller Output Signal OP) is NOT a function of the Process Variable (PV). The open loop control does not self-correct when the PV drifts, and this may result in large deviations from the optimum value of the PV.

4.4.1 Use of open loop control

This control is often based on measured disturbances to the inputs to the system. The most common type of open loop control is feedforward control. In this technique the control action is based on the state of a disturbance input without reference to the actual system condition, i.e. the system output has no effect on the control action, and the input variables are manipulated to compensate for the impact of the process disturbances (see Figure 4.3).

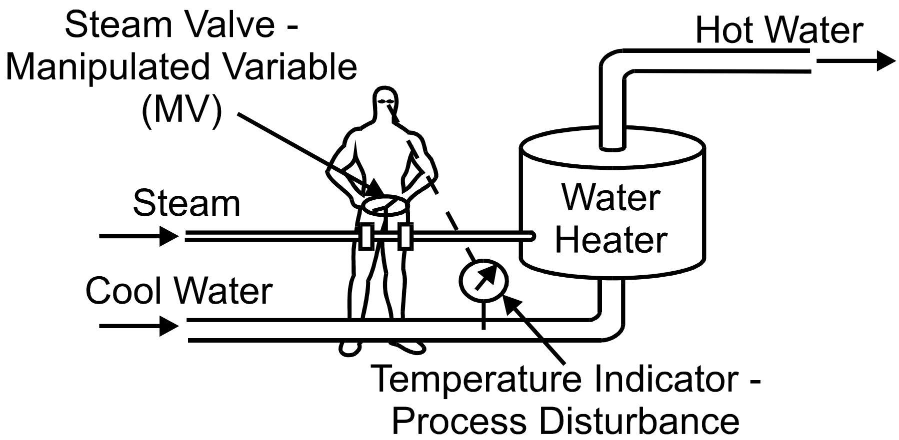


Figure 4.3
Concept of feed forward control

4.4.2 Function of open loop or feed forward control

Feedforward control results in a much faster correction than feedback control but requires considerably more information about the effects of the disturbance on the system, and greater operator skill.

4.4.3 Examples of open loop control

A common domestic application that illustrates open loop control is a washing machine.

The system is pre-set and operates on a time basis, going through cycles of wash, rinse and spin as programmed.

In this case, the control action is the manual operator assessing the size and dirtiness of the load and setting the machine accordingly.

The machine does not measure the output signal, which is the cleanliness of the clothes, so the accuracy of the process, or success of the wash, will depend on the calibration of the system.

An open loop control system is poorly equipped to handle disturbances which will reduce or destroy its ability to complete the desired task.

Any control system operating on a time base is an open loop. Another example of this is traffic signals.

It is difficult to implement open loop control in a pure form in most process control applications, due to the difficulty in accurately measuring disturbances and in foreseeing all possible disturbances to which the process may be subjected.

As the models used and input measurements are not perfectly accurate, pure open loop control will accumulate errors and eventually the control will be inadequate (see Figure 4.4).

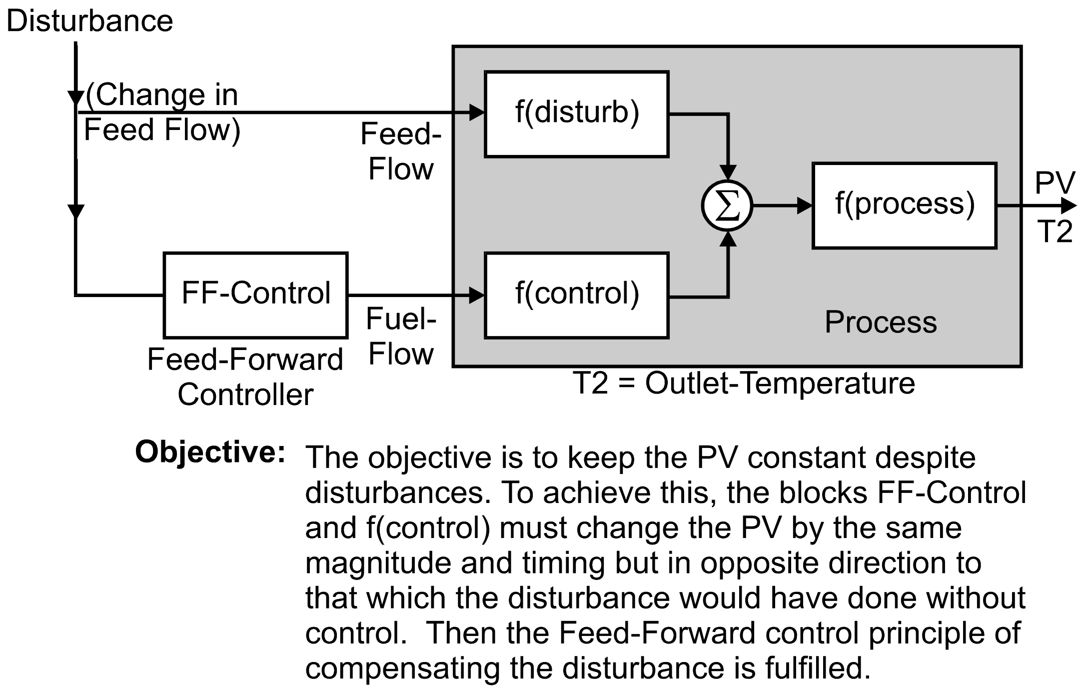


Figure 4.4
Feed forward block diagram

4.4.4 Introduction to ratio control

Ratio control, as its name implies, is a form of feedforward control that has the objective of maintaining the ratio of two variables at a specific value.

For example; if it is required to control the ratio of two process variables X_{PV} and Y_{PV} the variable PV_R is controlled rather than the individual PV's (X_{PV} and Y_{PV}).

Thus: $PV_{R} = X_{PV} / Y_{PV}$

A typical example of this is maintaining the fuel to air ratio into a furnace constant, regardless of maintaining or changing the furnace temperature. This is sometimes known as Cross Limiting Control.

4.5 Closed control loop

In closed loop control, the objective of control, the PV, is used to determine the control action. The concept of this is shown in Figure 4.6 and the principle is shown in Figure 4.7.

This is also known as feedback control and is more commonly used than feedforward control. Closed loop control is designed to achieve and maintain the desired process

condition by comparing it with the desired condition, the Set Point Value (SP), to get an Error Value (Err).

4.5.1 Reverse or direct acting controllers

As the controller's corrective action is based on the magnitude-in-time of the Error (ERR); which is derived from either SP-PV or PV-SP it is of no concern to the P, I or D functions of the controller which algorithm is used as the algorithms only change the sign of the Error term.

However; if we refer to Figure 4.5, which illustrates a controller, performing the same function, but in different ways:

In case one we Manipulate the OUTLET flow through V2 to control the tank level; this is **DIRECT** action.

Where as the PV increases (Tank Filling) the OP increases (Opening the outlet valve more) to drain the tank faster.

$$\text{Direct Acting} = \text{PV} \Uparrow \rightarrow \text{OP} \Uparrow \text{then } \text{Err} = \text{PV} - \text{SP}$$

In case two we control the INLET flow through V1 to control the tank level; this is **REVERSE** action.

Whereas the PV increases (Tank Filling) the OP decreases (Closing the inlet valve more) to reduce the filling rate.

$$\text{Reverse Acting} = \text{PV} \Uparrow \rightarrow \text{OP} \Downarrow \text{then } \text{Err} = \text{SP} - \text{PV}$$

The controller output changes, by the same magnitude and sign, based on the resultant Error value and sign.

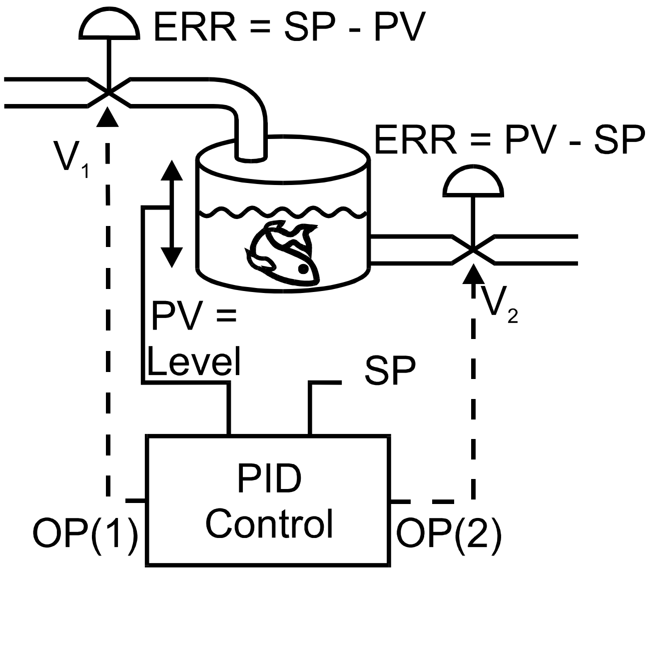


Figure 4.5
Direct and reverse acting controllers

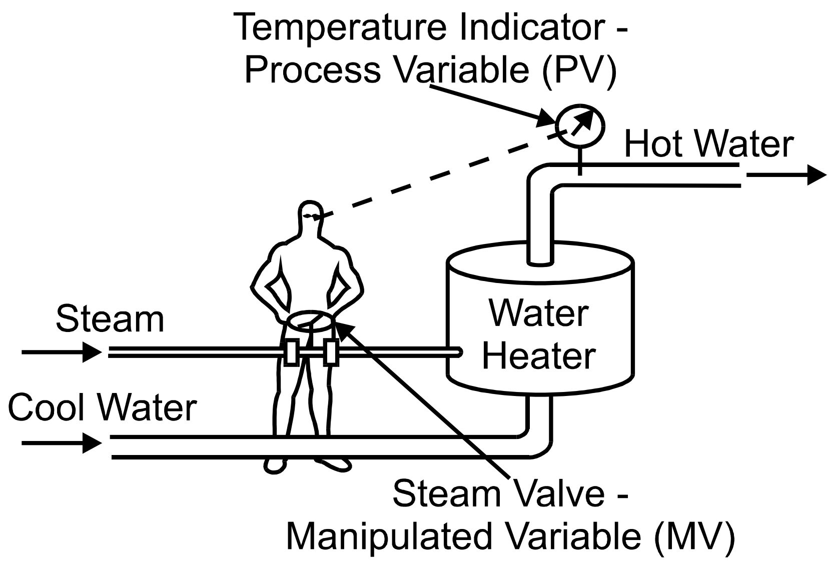


Figure 4.6
Manual feedback control

4.5.2 Control modes in closed loop control

Most closed loop controllers can be controlled with three control modes, either combined or separately.

These modes, Proportional (P), Integral(I), and Derivative (D), are discussed in depth in the next chapter.

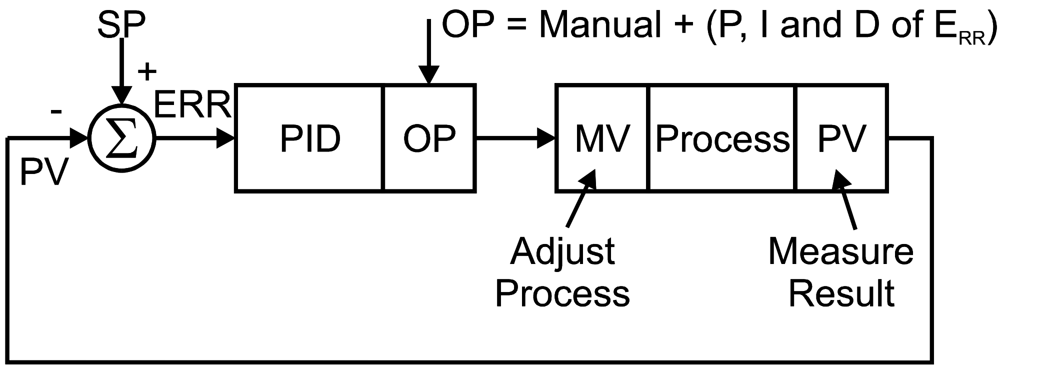
4.5.3 Illustration of the concepts of open and closed loop control

The diagrams in Figures 4.4 and 4.6 illustrate the concepts of open loop and closed loop controls in a water heating system.

In the open loop, feedforward example, the steam flow rate is varied according to the temperature of the cool water entering the system. The operator must have the skills to determine what change in the valve position will be sufficient to bring the cool water entering the system to the desired temperature when it leaves the system.

In the closed loop, feedback example, the steam flow rate is varied according to the temperature of the heated water leaving the system. The operator must determine the difference between that measurement and the desired temperature and change the valve position until this error is eliminated.

The above example is for manual control but the concept is identical to that used in automatic control, which should allow greater accuracy of control.



Process Gain $= \Delta PV / \Delta MV$

Controller Gain $= \Delta MV / \Delta E$(error)

LOOPGAIN(KLOOP) = K_C(Controller Gain) x K_P (Process Gain)

$= \Delta MV / \Delta E \times \Delta PV / \Delta MV = \Delta PV / \Delta E$

Figure 4.7
Closed loop block diagram

4.5.4 Combination of feedback and feedforward control

The advantages of feedback control are its relative simplicity and its potentially successful operation in the event of unknown disturbances. Feedforward control has the advantage of faster response to a disturbance in the input which may result in significant cost savings in a large-scale operation (see Figure 4.8).

In general, the best industrial process control can be achieved through the combination of both open and closed loop controls. If an imperfect feedforward model corrects for 90% of the upset as it occurs and the remaining 10% is corrected by the bias generated by the feedback loop, then the feedforward component is not pushed beyond its abilities, the load on the feedback loop is reduced, and much tighter control can be achieved.

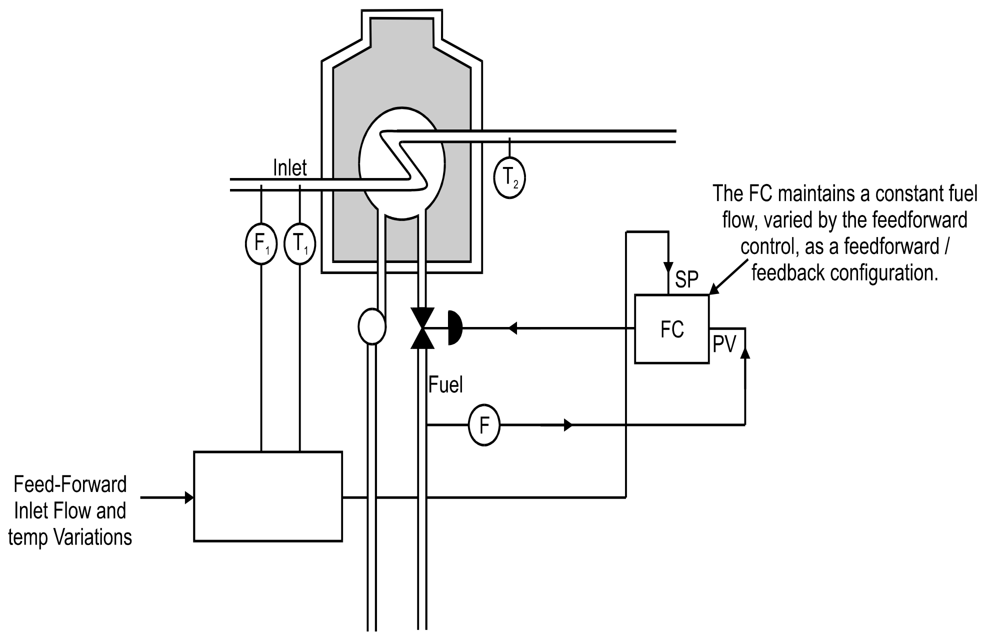


Figure 4.8
Block diagram of feedforward and feedback combination

4.6 Dead time processes

In processes involving the movement of mass, dead time is a significant factor in the process dynamics. It is a delay in the response of a process after some variable is changed, during which no information is known about the new state of the process. It may also be known as the transportation lag or time delay.

Dead time is the worst enemy of good control and every effort should be made to minimize it.

All process response curves are shifted to the right by the presence of dead time in a process (see Figure 4.9).

Once the dead time has passed, the process starts responding with its characteristic speed, called the process sensitivity.

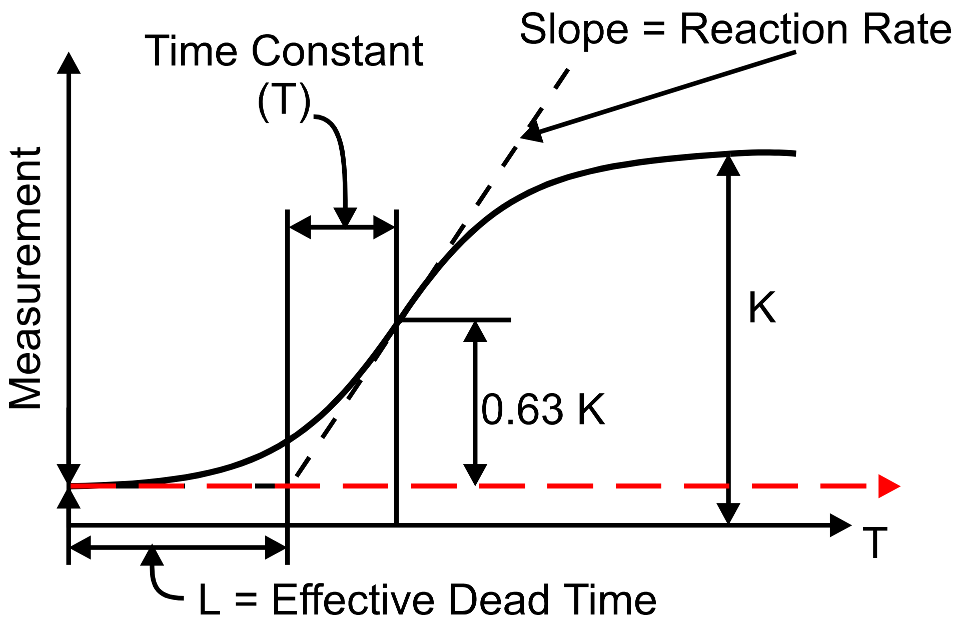


Figure 4.9
Process reaction or response curve, showing both dead time and time constant

4.6.1 Reduction of dead time

The aim of good control is to minimize dead time, and to minimize the ratio of dead time to the time constant. The higher this ratio, the less likely it is that the control system will work properly.

Dead time can be reduced by reducing transportation lags, which can be done by increasing the rates of pumping or agitation, reducing the distance between the measuring instrument and the process, etc.

4.6.2 Dead time effects on P, I and D modes and sample-and-hold algorithms

If the nature of the process is such that the dead time of a loop exceeds its time constant then the traditional PID (proportional-integral-derivative) control is unlikely to work, and a sample and hold control is used. This form of control is based on enabling the controller so that it can make periodic adjustments, then effectively switching the output to a hold state

and waiting for the process dead time to elapse before re-enabling the controller output. The algorithms used are identical to the normal process control ones except that they are only enabled for short periods of time Figure 4.10 illustrates this action.

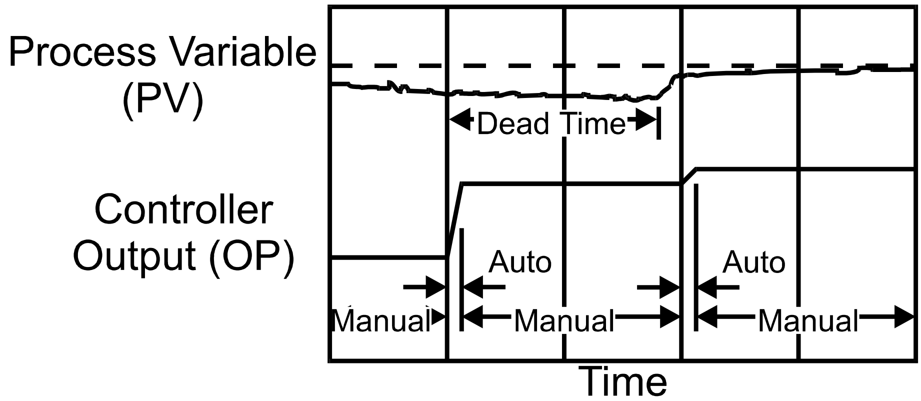


Figure 4.10
Sample and hold algorithms are used when the process is dominated by large dead-times

The only problem is that the controller has far less time to make adjustments, and therefore it needs to do them faster. This means that integral setting must be increased in proportion to the reduction in time when the loop is in automatic.

4.7 Process responses

The dynamic response of a process can usually be characterized by three parameters; process gain, dead time and process lag (time constant) (see Figure 4.11).

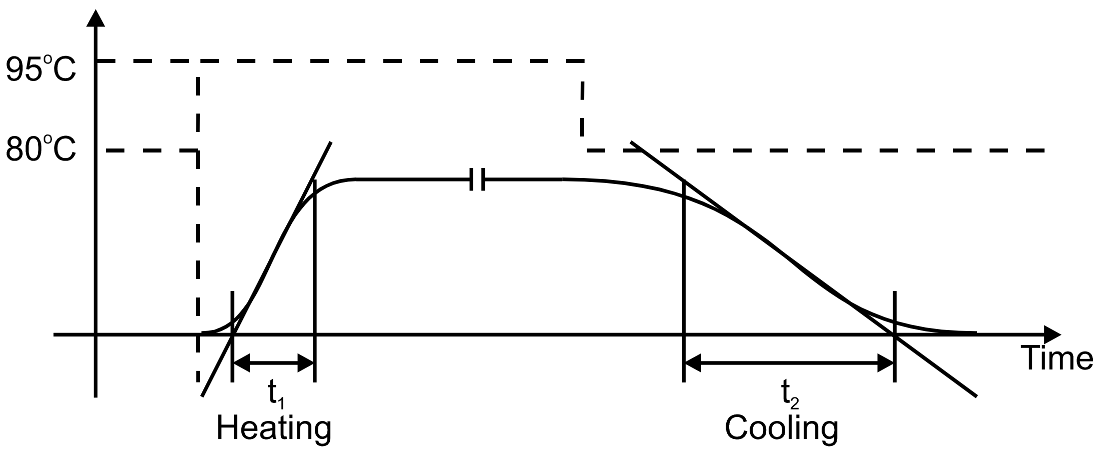


Figure 4.11
Example of a process response related to a step change of the input value

The following sections define the three constitutional parts of the process response curve as illustrated in Figure 4.10.

4.7.1 Response process gain

The process gain is the ratio of the change in the output (once it has settled to a new steady state) to the change in the input. This is the ratio of the change in the process variable to the change in the manipulated variable,

It is also referred to as the process sensitivity, as it describes the degree to which a process responds to an input.

A slow process is one with low-gain, where it takes a long time to cause a small change in the MV. An example of this is home heating, where it takes a long time for the heat to accumulate to cause a small increase in the room temperature. A high gain controller should be used for such a process.

A fast process has a high gain, i.e. the MV increases rapidly. This occurs in systems such as a flow process or a pH process near neutrality where only a droplet of reagent will cause a large change in pH. For such a process, a low gain controller is needed.

The three component parts of process gain , from the controllers perspective is the product of the gains of the measuring transducer (K_S), the process itself (K_C) and the gain of what the PV or controller output drives (K_V).

This becomes: Process Gain = K_S x K_c x K_V

4.7.2 Response dead time

The dead time (L) is the delay between the manipulated variable changing and a noticeable change in the process variable.
Dead time exists in most processes because few, if any, real world events are instantaneous. A simple example of this is a hot water system. When the hot tap is switched on there will be a certain time delay as hot water from the heater moves along the pipes to the tap. This is the dead time.

4.7.3 Response process lag

The process lag (T) is caused by the system's inertia and affects the rate at which the process variable responds to a change in the manipulated variable.

It is equivalent to the time constant.

4.8 Dead zone

In most practical applications, there is a narrow bandwidth due to mechanical friction or arcing of electrical contacts through which the error must pass before switching will occur.

This may be known as the dead zone, differential gap, or neutral zone.

The size of the dead zone is generally 0.5% to 2% of the full range of the PV fluctuation, and it straddles the Setpoint.

When the PV lies within the dead zone no control action takes place, thus its presence is usually desirable to minimize the cycling of the process. One problem with on-off control is wear and tear of the controlling element. This is reduced as the bandwidth of fluctuation of the process is increased and thus frequency of switching decreased.

Practical Exercise

The following exercise is suitable for gaining some practice with basic closed loop control as described in this chapter. Refer to Appendix D.

Exercise 2 – Flow Control Loop – Basic Example for Closed Loop Control